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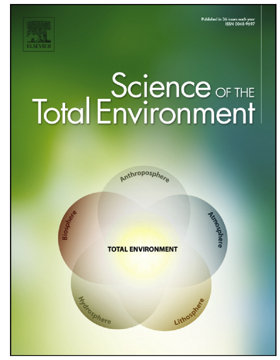

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Effect of N dose on soil GHG emissions from a drip-fertigated olive (*Olea europaea* L.) orchard

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Abstract

Agronomic practices may mitigate greenhouse gas emissions (GHG) from crops. Appropriate nitrogen (N) and irrigation management provide the potential to reduce nitrous oxide (N_2O) and methane (CH_4) emissions. However, there is little information about the combination of both practices on the GHG emissions from olive orchards. This four-year study was conducted to qualitatively compare the effect of N doses applied through two drip irrigation strategies on N_2O and CH_4 emissions in a super-intensive (1010 trees ha^{-1}) olive orchard. The design (randomised blocks) was asymmetric: 0, 50 and 100 kg N ha^{-1} yr^{-1} were tested with full irrigation (FI; 2013 to 2016), but only 0 and 50 kg N ha^{-1} yr^{-1} were tested with regulated deficit irrigation (RDI; 2014 to 2016). The study shows that the soil acted as a main sink of N_2O and CH_4, regardless of the soil water content. Methane oxidation increased with N dose in the FI strategy (significant in 2013 and 2015). Overall, there was a tendency of yield to increase with the N dose without increasing emissions and without depending of the irrigation strategy. However, these results were not significant. Further confirmation of

this tendency is necessary; particularly comparing FI+N100 (most promising treatment in terms of profitability) with the RDI+N100 (not available in this study) water-saving strategy.

Keywords: N_2O consumption, CH_4 oxidation, regulated deficit irrigation, super-intensive olive orchard, greenhouse gas intensity

1. Introduction

Agriculture is responsible for 52% and 84% of global anthropogenic emissions of methane (CH_4) and nitrous oxide (N_2O), respectively (Smith et al., 2008). Emissions of N_2O have been associated with stratospheric ozone destruction (Chapuis-Lardy et al., 2007). Different agricultural practices (irrigation, tillage, etc.) can affect greenhouse gas (GHG) emissions (Sainju et al., 2012). The emission or consumption of these agricultural GHGs is mainly controlled by the water-filled pore space (WFPS) and the soil content of ammonium (NH_4^+) and nitrate (NO_3^-) (Le Mer and Roger, 2001; Ussiri and Lal, 2013; García-Marco et al., 2014).

Aerobic agricultural soils, both rain-fed and irrigated, promote CH_4 oxidation, which is very dependent on management practices such as N fertilisation (Sanz-Cobena et al., 2017). The effect of fertiliser application rate on soil CH_4 uptake has been found to be positive (Meijide et al., 2017 in Sanz-Cobena et al., 2017), negative (Guardia et al., 2016 in Sanz-Cobena et al., 2017) or neutral (Plaza-Bonilla et al., 2014 in Sanz-Cobena et al., 2017). The indirect evidence of anaerobic activity (as methanogenesis) in relatively well-drained soils has also been observed and has been related to the presence of anoxic microsites (Brewer et al., 2018). Regarding N_2O, there is general agreement on the main role played by nitrification and denitrification in its production from soil (Azam et al., 2002; Menéndez et al., 2008; Jamali et al., 2016; Tang et al., 2019), although other microbial processes also contribute to its emission (Butterbach-Bahl et al., 2013). Nitrification is typically associated to aerobic conditions while denitrification is considered to be predominant under wet conditions (>70% WFPS) (Khalil and Baggs, 2005). However, both processes may occur simultaneously due to the presence of microsites that can develop within the same aggregate (Azam et al., 2002).

Inorganic and organic fertiliser can provide the necessary substrates for the N_2O production from microbial nitrification and denitrification processes (Dong et al., 2018). Nonetheless, it is also reported that low mineral N contents and soil high moisture content could favour the consumption of this gas due to its reduction to N_2 through denitrification (Frasier et al., 2010). According to Castaldi and Aragosa (2002) low available mineral nitrogen (N) in soil could limit the rate of both microbial processes.

Therefore, optimising agricultural practices such as irrigation and N dosing could enhance the soil potential to act as a GHG sink and contribute to meeting the commitment established during the Paris Agreement (2015) of reducing these emissions by at least 40% by 2030 (European Commission, n.d.).

The olive tree (*Olea europaea* L.), a crop well adapted to drought, is ancient and widespread in the Mediterranean Basin where 95% of the worldwide production of this crop is concentrated (EUROSTAT, 2018). Spain is the world's leading olive oil producer with more than 2.6 million ha of olive trees under cultivation, corresponding to 45% of worldwide olive production and 59% of EU production (MAPA, 2018; MAPA, n.d.a; EUROSTAT, 2018). With this crop, Spain generated an economic input of 1,886 million Euros on average from 2007 to 2012 (MAPA, n.d.a).

The health benefits associated with the consumption of virgin olive oil have caused an increase in the demand for this product in recent decades (Ahumada-Orellana et al., 2018). This scenario has led to an increase in oil production, which has been achieved through various crop intensification techniques. In the last two decades, the so-called super-high-density (SHD) system has been implanted worldwide (Tous et al., 2014). Arbequina is considered the predominant cultivar for this kind of plantation (De la Rosa et al., 2007; Rufat et al., 2014; Díez et al., 2016). These densely planted olive orchards permit a major mechanisation of the production process, but also increase irrigation and fertilisation requirements (Cameira et al., 2014).

Taking into account the context of climate change and the scarcity and high cost of water in many olive-growing areas, using irrigation strategies such as drip irrigation (DI) or regulated deficit irrigation (RDI) that reduce water consumption is of great interest (Egea et al., 2017). In addition, it provides an opportunity to reduce the degradation of water quality in the rivers due to water use for irrigation (Hillel et al., 2015). The RDI strategy has been studied in the last twenty years for its environmental and economic impact in the agronomic sector. According to Ahumada-Orellana et al. (2017), beyond a reduction of 25% of the water crop needs the yield can be penalised. However, other authors did not observe important yield reductions with a water reduction of 45% of the crop needs (Goldhamer, 1999). Gucci et al. (2019) tested two RDI strategies (with 36% and 43% water reduction in comparison to full irrigation) in a

SHD olive orchard (cv. Frantoio) and observed a slight decrease in yield, although yield efficiency was similar in all the studied treatments. Grattan et al. (2006) applied several deficit irrigation strategies based on variations ranging from 15% to 140% of the crop evapotranspiration (ETc), and found that high oil yield can be achieved in a broad range of applied water regimes. Other authors have observed an increase in oil yield with a moderate RDI (Rosecrance et al., 2015). In conclusion, there is no general consensus about the effect of irrigation reduction on the olives yield nor on the olive oil yield.

In this sense, DI combined with the split application of N fertiliser dissolved in the irrigation water (i.e. drip fertigation) is considered a good strategy for a high water use efficiency and increased N use efficiency (Darwish et al., 2006; Abalos et al., 2014). Moreover, reducing the water supply could mitigate N_2O emissions by limiting the amount of water available for microorganism activity (Steenwerth and Belina, 2010; Kennedy et al., 2013). A moderate soil WFPS could also stimulate CH_4 oxidation (Serrano-Silva et al., 2014). However, there is not much information available on the effect of these drip fertigation strategies on GHG emissions in tree crops.

Nitrogen supply is another factor of great importance in the quality and quantity of olives and olive oil. Traditionally, olive trees have not been considered big N consumers (Therios, 2009) and the recommendations for fertigation are scarce (Erel et al., 2018). However, according to Fernández-Escobar et al. (2014), the relatively low cost of N fertilisers and the perception that higher amounts of N fertilisation result in higher yields can often lead to over-fertilisation. Perhaps for these reasons, in Spain the N fertilisation application to olive orchards varies considerably from 9 to 350 kg N ha^{-1} yr^{-1} (Fernández-Escobar et al., 1994 in Fernández-Escobar et al., 2009), though tree density is unknown. In fact, there is no general agreement about the effect of the N dose on yield (Table 1).

Some authors have reported that increasing N could reduce olive oil quality (Morales-Sillero et al., 2007; Centeno et al., 2017). However, other authors have found no significant differences in this respect (Marcelo et al., 2010).

The literature on the effect of N fertilisation and RDI strategies on olive tree parameters (vegetative growth, yield, quality of olive oil, etc.) is quite extensive, but few authors have studied both factors at the same time.

Despite the ongoing intensification of olive cultivation, there is a gap in the knowledge regarding the effect of N fertilisation and irrigation strategies on GHG emissions for this crop. We could find only one publication on the subject: Maris et al. (2015) who tested two N doses (0 and 50 kg N ha^{-1}) with and without nitrification inhibitor and with two irrigation strategies (FI: full irrigation, and SDI, which worked in a similar way to the RDI of this study) in the same olive orchard of this study.

According to Shcherbak et al. (2014), there is a tendency of exponential increase instead of linear in the emission of N_2O in response to additions of N fertiliser. Bouwman (1996) observed almost constant N_2O emissions below 100 kg N ha^{-1}, whereas they increased along with the increase in the N dose for applications above 100 kg N ha^{-1}. It is estimated that for every 100 kg N ha^{-1} applied, 1 kg N_2O is emitted directly from soil (IPCC, 2006). In any case, a lower N application impact on N_2O emissions would be expected if N application is adjusted to crop needs.

In light of the existing gap in the literature, we hypothesised that increasing N dose in a super-intensive olive orchard would increase N_2O and CH_4 emissions and that an RDI strategy would reduce them relative to FI. Therefore, the objective of the present study was to qualitatively compare the effect of different N doses applied through different irrigation strategies on the N_2O and CH_4 emissions from a super-intensive olive orchard.

2. Material and methods

2.1. Site description

The study was conducted in Torres de Segre (Lleida, NE Spain; see Maris et al. (2015) for further site details), at a 2.52 ha commercial SHD adult olive orchard (*Olea europaea* L. cv. Arbequina) during the years 2013-2016.

The climate is continental Mediterranean, with an average annual rainfall of 333 mm, irregularly distributed, and an average (2006 to 2016) annual temperature of 15.1 ºC (with an average minimum and maximum temperature of 3.6 ºC and 27.0 ºC, respectively). Average wind speed is 2.14 m s^{-1} and average relative humidity is 64%. Air temperature and rainfall were obtained from the closest meteorological station located at Torres de Segre (Meteorological Service of Catalonia, n.d.). Each sampling day, soil temperature (at a depth of 10 cm) was measured in the field.

The soil is shallow to moderately deep. The dominant soil type at the site is a Typic Calcigypsids (SSS, 2014). Table 2 shows the average results of the soil analysis at the beginning of the study from the gas sampled plots.

2.2. Experimental design

The trees were planted at a spacing of 4.5 m × 2.2 m in summer 2002, with a final density of 1010 trees ha^{-1}. The experiment had a completely randomised block design with two irrigation strategies and different N doses. There were four blocks, of which only three were sampled. In each block there were 18 trees per treatment distributed in three adjacent rows in which the four central trees were monitored (Rufat et al., 2014).

The irrigation strategies were:

Full Irrigation (FI): 100% of the water requirements were applied throughout the cropping season (mid-April to mid-October),

Regulated Deficit Irrigation (RDI): only 70% of the total crop requirements were applied throughout the cropping season according to the following scheme: mid-April to June, 100% of the water requirements; July to September 11th, 40% of the water requirements; September to mid-October, 100% of the water requirements.

Water requirements for both irrigation strategies were determined according to the FAO methodology (Allen et al., 1998) and the crop coefficient values (Kc). The optimal Kc to produce olive oil (~0.68) was established by Girona et al. (2002). Monthly ETo, rainfall and irrigation are detailed in Table 3. The trees were irrigated daily.

The irrigation system consisted of auto-compensated drip emitters located every 60 cm, with a flow rate of 2.3 L h^{-1} (Rufat et al., 2014). The water for irrigation was taken from the river Segre and had the following characteristics: a water conductivity of 0.9 dS

m^{-1}; a chloride content of 2.25 meq L^{-1}; a sodium content of 2.14 meq L^{-1}; a nitrate content of 9 ppm, and a boron content of <0.15 ppm (Rufat et al., 2014).

The N treatments applied were: N0: no N application; N50: 50 kg N ha^{-1}; and N100: 100 kg N ha^{-1} per cropping season (year). The N0, N50 and N100 treatments were applied with the FI strategy, while with the RDI strategy only the N0 and N50 treatments were applied. The appropriate fertilising units per hectare were applied once a week through fertigation with an N20 fertiliser (50% ammonium and 50% nitrate; facilitated by COMPO EXPERT Spain S.L.) and with 100 kg K_2O ha^{-1} (potassium solution 0-0-15) according to a monthly plan from April to October each year (Table 3). Due to the high initial soil phosphorus content, no phosphate fertilisation was applied during the four-year study.

2.3. Gas sampling and analysis

The sampled treatments were:

FI+N0, FI+N50 and FI+N100 during the four study years and;

RDI+N0 and RDI+N50 in 2014, 2015 and 2016.

Gas monitoring was done only on three of the four experimental blocks. Gas sampling was performed weekly during the irrigation period (which is longer than fertigation).

Undisturbed soil cores were taken using PVC tubes (16.5 cm long and 7 cm diameter) from the wet soil surface of the bulb generated by irrigation. Three replicates per block were collected with a total of nine cores per treatment. The soil cores were placed in an insulated enclosed cage and transported rapidly to the laboratory (15 minutes by car).

Some authors, including Hütsch et al. (1994) and Hangs et al. (2013) have used a similar sampling method to collect the samples in the field.

In the laboratory, each soil core was placed in a transparent glass jar of 1.5 L equipped with an airtight glass lid. In the lid of each jar was a hole with an airtight three-way key which was directly connected via a Teflon® tube to the photoacoustic analyser (Innova 1412 Photoacoustic Multigas Monitor). After closing the lid, the air samples inside the glass jar were extracted at regular intervals of 0, 20 and 40 minutes. The nitrous oxide (N_2O) and methane (CH_4) daily fluxes were obtained using the semi-static closed chamber technique (Burford and Hall, 1977; Livingston and Hutchinson, 1995), and were determined from the linear increase or decrease of the gas concentration through time.

After forty minutes of sampling, the glass jar lids were emptied and left open for a few minutes to allow equilibrium between internal and external gas concentrations and pressures before proceeding with the following measurement (Maris et al., 2015).

Cumulative emissions throughout the study period were calculated by integrating the daily fluxes over time.

Since the photoacoustic analyser refers the gas concentration to 20°C and 1 atm, the gas concentration was corrected to the average field temperature and atmospheric pressure (recorded from the nearest meteorological station) of each day of sampling. The sampling was carried out at 10 a.m. in order to minimize any over- or under-estimation of the emission caused by the daily variation of soil temperature (Maris et al., 2015).

The detection limit of the photoacoustic analyser is 0.03 ppm for N_2O and 0.40 ppm for CH_4.

All the results are expressed as mass of each gas emitted during the day (daily fluxes) or sampling period (cumulative emissions) and per hectare. The daily fluxes and cumulative emissions are expressed as mass per hectare and per time. It should be kept in mind that only 1/15 (6.66%) of the field surface was wet. The daily GHG fluxes and emissions presented refer only to the surface of the wet bulb generated by fertigation.

2.4. Soil sampling and analysis

Once the gas analysis had been concluded, the soil samples were dried at 105°C during 48 h. The WFPS was calculated by dividing water content (expressed in volume) by total soil porosity. To calculate total soil porosity, soil bulk density was calculated applying the following relationship:

$$\text{Soil porosity} = 1 - (\text{soil bulk density}) / \text{PD}$$

where PD is mean particle density, which for most mineral soils is assumed to be 2.65 g cm^{-3}.

A composite soil sample (0.25 cm depth) was taken from each elementary plot at the beginning and end of each cropping season to determine the soil NO_3^--N content (except in 2016), which was measured by colorimetry. The NH_4^+-N content was not determined because low values had been obtained in the site in previous years.

2.5. Harvesting

Harvesting was performed in November in 2013 and 2016. In 2015, due to unusually warm conditions in late spring (June; Table 4, see supplementary material), harvesting took place earlier at the end of October. In 2014, the olive harvest was not quantified as it had been severely damaged by bad weather. Harvesting was carried out using a grapevine machine adapted for olive tree hedgerows (Rufat et al., 2014).

2.6. Calculations

The direct N_2O emissions and CH_4 oxidation were converted to global warming potential (GWP: units of carbon dioxide equivalent (CO_2-eq) within a 100-year horizon) by multiplying by a radiative forcing potential equivalent to CO_2 of 265 for N_2O and 28 for CH_4 (IPCC, 2013). The greenhouse gas intensity (GHGI) was calculated by dividing the GWP by crop yield (production of olive oil for olive crop) (Mosier et al., 2006).

2.7. Statistical analysis

The normal distribution of the fluxes (N_2O and CH_4) was verified using the Shapiro–Wilk test. The homogeneity of the variance was assessed with the Levene test. The cumulative emissions of N_2O and CH_4 were examined with an ANOVA model (JMP, Version 13), taking into account the irrigation strategy (I), the fertiliser dose (N), and their interaction (I×N). The interaction between irrigation strategy and N dose was assessed only for the 0 and 50 kg N ha^{-1} doses. The multiple comparisons between means ($p<0.05$) were assessed with Tukey's test and the Student's t-test.

In order to evaluate the correlation between GHG emissions and the studied variables (i.e. soil temperature, air temperature and WFPS) the non-parametric Spearman rank coefficient was used with a statistical significance of $p<0.05$.

3. Results

3.1. Water-filled pore space (WFPS) and air and soil temperature

During the irrigation period, the WFPS varied between years. The lowest WFPS (40 to 60%) was registered in 2013, an average year in terms of precipitation (Fig. 1a). In 2014 (Fig. 1b), the year with the highest precipitation, the WFPS remained mainly above 80% until the beginning of September (day 110). The WFPS peak, recorded on day 135 of sampling, corresponds to intense rains and hail in some cases. In 2015 (Fig. 1c), the WFPS ranged from 25% to 60%, except in the FI+N0 treatment where the WFPS was higher throughout the sampling period. The decrease observed between sampling days 65 and 80 was due to a rise in temperature. The decrease observed from day 110 on was associated with the decrease in the water supply and after day 138 to the cessation of irrigation. In 2016 (Fig. 1d), all treatments (except FI+N0 which presented higher values throughout the sampling period) had WFPS values between 40 and 70%. The variability of the determined WPFS values was attributed to the heterogeneity of the soil site (depth, organic matter content, different soil orders coexisting in the field -though the dominant one has been mentioned- and the local topography).

The range of temperatures during the study years is shown in Table 4 (see supplementary material). The lowest average soil temperature (13.0 ºC) was recorded in

2016 and the highest in 2015 (24.1 ºC; Table 4, see supplementary material). Both the lowest and highest air temperatures were recorded in 2015 (1.2 ºC and 40.7 ºC). The highest ETo (935 mm) and the lowest precipitation (149 mm) during the cropping season were in 2015 (Table 3).

3.2. Daily fluxes of nitrous oxide

Daily N_2O emission fluxes (Fig. 2a) in 2013 ranged between -40 and 20 g N_2O-N ha^{-1} d^{-1} throughout the sampling period. After day 54, there was a decrease in emissions, associated with the cessation of fertilisation at the end of June. Emissions increased slightly from day 115 onwards when fertilisation had already been resumed.

In 2014 (Fig. 2b), daily N_2O fluxes for all treatments were quite homogeneous. Between days 75 and 120, the emissions were mostly negative in all treatments. This was related to the cessation of fertilisation in summer. After day 112, when fertilisation was resumed, the emissions increased slightly.

The daily emission fluxes of N_2O in 2015 (Fig. 2c) were positive until day 25, except for the N0 treatments. From June to the end of the sampling period the emissions were about zero, although there were 17 kg N ha^{-1} applied between days 100 and 130 (September). In the same year, N_2O emissions correlated significantly with soil and air temperature (ρ=0.36 and 0.32, respectively).

In 2016, the daily fluxes of N_2O were low and ranged between -8 and 6 g N_2O-N ha^{-1} d^{-1} (Fig. 2d). The fertilised plots presented N_2O emissions until day 60 of sampling when fertigation was stopped.

3.3. Cumulative nitrous oxide emissions

In all the studied years, the soil acted mostly as an N_2O sink (Table 5). There were significant direct N_2O emissions in 2013 from the FI+N50 treatment which could be related with the NO_3^--N content (Fig. 3). Except for the FI+N0 and FI+N50 treatments in 2013, the FI+N50 in 2015 and the FI+N0 in 2016, the NO_3^--N content was similar among treatments. In 2013, the FI+N100 treatment had the largest negative emissions (almost -2 kg N_2O-N ha^{-1}; Table 5). In 2015, the FI+N50 and FI+N100 treatments had positive cumulative N_2O emissions. For the rest of the studied years and treatments, the cumulative N_2O emissions were negative (Table 5). In 2015, fertilisation significantly increased N_2O emissions relative to the control (Table 6).

Both irrigation strategies showed negative emissions (Table 6). Analysing the cumulative emissions of the four studied years together (Table 5), the soil acted as an N_2O sink for all treatments, even at the highest N dose.

3.4. Methane fluxes and cumulative emissions

There was methane (CH_4) oxidation all years from all the treatments. In 2013, 2014 and 2016, the soil acted as a sink for CH_4 for all the treatments (Table 7). In 2015, cumulative CH_4 emissions were positive (low values) for the FI+N0, FI+N50, and RDI+50 treatments.

In 2013 and in 2014, CH_4 daily fluxes (Fig. 4a and 4b) were negative throughout the sampling period. The FI+N100 treatment presented the most negative flows. In that year, CH_4 flows were positively correlated with the WFPS (0.20; $p<0.05$).

In 2015, there was a negative peak on day 26 (Fig. 4c) corresponding to a WFPS above 60%. From day 40 until the end of the sampling period, the CH_4 fluxes remained close to zero. In 2016 (Fig. 4d), the fluxes were negative and close to zero during the entire sampling period. In that year, CH_4 correlated positively with the WFPS (0.21, $p<0.05$).

In 2013, a higher N dose increased CH_4 oxidation relative to the control (Table 8). In 2014, there was no visible effect of fertilisation on CH_4 oxidation. In 2015 fertilising significantly increased CH_4 oxidation relative to the control, but only for the N100 dose. Regarding the effect of irrigation strategy, in 2014 and 2016 there was no clear effect (Table 8). In 2015, the RDI strategy significantly increased CH_4 oxidation.

In the global analysis of the four studied years it can be seen that, in the FI treatments, a higher application of N tended to higher CH_4 oxidation (Table 7), though this was significant only for the FI+N100 treatment.

3.5. Global warming potential, yield and greenhouse gas intensity

The global warming potential (GWP) calculation gives information about the potential mitigation of a treatment in units of CO_2 equivalent. In all the studied years, this parameter ranged from -13025 to 1715 kg CO_2-eq ha^{-1} (Table 9). In 2013 and 2015, the GWP for the FI+N100 treatment was significantly lower ($p<0.05$) than for the FI+N50 treatment and for the RDI+N50 treatment (only in 2015).

Regarding yield (expressed as oil production), the maximum was obtained in 2013 from the FI+N50 treatment (Table 9). In 2015, yield was low (off-year). The year 2016 was a year of high production with the FI+N100 treatment giving the highest yield, though not significantly different from the RDI+N0 treatment.

The greenhouse gas intensity (GHGI) was mainly negative for the three years of data. The GHGI of the FI+N100 treatment was significantly the lowest in 2013, as was also the case in 2015 together with the FI+N0 and RDI+N0 treatments (Table 9).

4. Discussion

4.1. Nitrogenous emissions

The N_2O fluxes were relatively low and predominantly negative in all the studied years due to the low N doses applied through fertigation, which permits efficient crop nutrition. There is a limited understanding of factors regulating N_2O consumption (Chapuis-Lardy et al., 2007), although nitrate (NO_3^--N) availability has been pointed out as the most obvious factor. Bacteria can use N_2O as an electron acceptor when the concentration of other forms of nitrogen oxides is too low (Rosenkranz et al., 2006).

This is consistent with the low NO_3^--N content (Fig. 3) recorded in the soil in this study, below 20 mg NO_3^--N kg^{-1} in all studied years and mostly below 5 mg NO_3^--N kg^{-1} from fertilised plots. In a previous study conducted in the same field by Belguerri et al. (2016) there was no leaching neither in the control nor in the 50 kg N ha^{-1} treatment. They collected the soil samples for the analysis of NO_3^--N content at 90 cm depth, considered the free drainage depth. The N budget carried out by Belguerri et al. (2016) was negative. This suggests that probably the olive trees did uptake most of the N fertiliser, reducing the NH_4^+ and NO_3^- which could favour direct N_2O emissions as a by-product of the nitrification and denitrification microbial processes. According to Chapuis-Lardy et al. (2007), a low available NO_3^--N content, as in this study, could favour N_2O consumption.

According to Buchen et al. (2019), N_2O consumption could also be favoured when the WFPS is high. This was observed in 2014 in the present study. However, other authors such as Longoria-Ramírez et al. (2003) found that net consumption of N_2O occurred at a WFPS between 46 and 70%, which covers the WFPS ranges in 2013, 2015 and 2016 in the present study (Fig. 1).

Soil microbiota can produce and consume N_2O. The final N_2O flux is a result of the balance between the two offsetting processes which determine which products predominate. In this study, most likely due to moisture content, N_2O consumption was the main process with a cumulative N_2O emission ranging between -1.9 and -0.2 kg N_2O-N ha^{-1} (Table 5). Aguilera et al. (2015) reported higher direct N_2O emissions (0.10 and 0.11 kg N_2O ha^{-1} yr^{-1}) in conventional and organic olive orchards. One possible explanation for these negative emissions could be that in moderately fine textured soils, such as the one of this study, soil diffusivity would be reduced. This in turn would limit the physical exchange of N_2O (Christiansen and Gundersen, 2011), which would favour consumption of this gas in the soil. In the years with lower WFPS, there were cumulative N_2O emissions only from the FI+N50 treatment in 2013, and from the FI+N50 and FI+N100 treatments in 2015. This suggests that, in spite of the presence of microsites where both nitrification and denitrification could take place, in the years in which the WFPS was favourable to nitrification (25-60%) there were only N_2O emissions from fertilised plots. These N_2O emission values were similar to those published by Maris et al. (2015) in the same study site, but lower than those reported by Cayuela et al. (2017) (1.2 kg N_2O-N ha^{-1}) for Mediterranean perennial crops including olive trees, almonds and vineyard but also citrus and other fruit trees.

Less negative cumulative N_2O emissions than those presented in this study have been reported by Schlesinger (2013) and Shvaleva et al. (2015). Several authors have reported N_2O consumption in the soil (Chapuis-Lardy et al., 2007; van Groenigen et al., 2015; Ye and Horwath, 2016). However, none of these are from olive trees in Mediterranean conditions. There are very few articles which have reported N_2O consumption from Mediterranean crops, and only two (Aguilera et al., 2015 and Maris et al., 2015), to our knowledge, which have reported N_2O emissions (in whatever sense) from olive trees.

4.2. Effect of the irrigation strategies and nitrogen doses on the nitrogenous emissions

The N_2O emissions were significantly more negative when decreasing the amount of water supplied (RDI strategy; Table 6), but only in year 2015. Similar results were reported by Maris et al. (2015) for the same study site for another cut-off irrigation strategy (SDI functioning in a manner equivalent to RDI). Fentabil et al. (2016) also found a decrease in N_2O emissions in an apple orchard under low frequency drip irrigation compared with a high frequency one.

Regarding the N dose, the effect varied depending on the year. In 2013, N_2O consumption was higher with higher N dose, but in 2014 and 2015 (statistically significant; Table 6) N_2O consumption was lower when N dose increased. There was no net cumulative N_2O emission in any year, except in 2015 from the N100 dose (Table 6). Fentabil et al. (2016) found no statistical differences in N_2O emissions between low and high N fertilisation in an apple orchard. On the other hand, Schellenberg et al. (2012) found lower N_2O emissions when irrigating without fertiliser, which is in agreement with the lower N_2O emissions recorded in this study after the fertigation period.

4.3. Methane oxidation

The olive orchard acted as a net CH_4 sink for all the treatments and years, except for the FI+N0, FI+N50 and RDI+N50 treatments in 2015, which had low CH_4 emissions (Table 7). Year 2015 was especially warm during late spring and the vegetative growth of the crop was ahead of time. Negative CH_4 emissions were also found in other studies conducted in melon plantations under drip irrigation (Vallejo et al., 2014; Abalos et al., 2014) and in afforested soils in Denmark (Christiansen and Gundersen, 2011). According to Hu et al. (2013), moderate WFPS (20-60%), as in 2013 and 2015 in the present study, is the optimal range for CH_4 oxidation by soil. In 2014 the WFPS was higher (40 to 90%), and in 2016 it was between 40 and 70%. In fact, CH_4 production requires strict anaerobic conditions and correlates positively with soil humidity (Oertel et al., 2016), a condition that did not happen in most of this study. A decrease in soil moisture enhances CH_4 oxidation through improved O_2 diffusion from the atmosphere into the soil pore spaces and through improved gas diffusivity (Ball et al., 1997; Tate, 2015). According to Le Mer and Roger (2001), non-flooded upland soils (e.g. forests, cultivated soils, etc.) are considered biological sinks of atmospheric methane.

Regarding the effect of the irrigation strategy (Table 8), in 2015 cumulative CH_4 oxidation from the RDI was significantly higher than from the FI treatment. This could be due to the lower WFPS of that year (Fig 1c). At higher WFPS (years 2014 and 2016), no effect of the irrigation strategy on CH_4 emission could be observed.

As for the effect of the N dose (Table 8), there was a tendency to higher CH_4 oxidation (with small amounts from all the treatments) when increasing the N dose, though it was significant only in 2013, and in 2015 between the control and N100. Some authors have reported that high nitrate soil content could reduce CH_4 oxidation (Hütsch, 2001; Le Mer and Roger, 2001). However, this inhibition could have a lesser impact on CH_4 oxidation if the nitrate concentration is not very high (Bodelier and Laanbroek, 2004), as in the present study. In addition, Schellenberg et al. (2012) found the highest CH_4 oxidation from higher N fertiliser inputs (67 kg N ha^{-1}) in some cases. Aronson and Helliker (2010) reported that smaller amounts of N tended to stimulate CH_4 uptake while larger amounts tended to inhibit uptake by the soil. When all other variables were accounted for, the switch occurred at 100 kg N ha^{-1} yr^{-1}.

Analysing the four years together (Table 7), within the FI strategy CH_4 oxidation significantly increased with the N dose. This concurs with the results of Bodelier et al. (2000) and Mohanty et al. (2006). However, other studies on other crops (Abalos et al., 2014; Sun et al., 2016) have reported the opposite (that higher N doses stimulate CH_4 emission).

4.4. Global warming potential, yield and greenhouse gas intensity

In this olive orchard, the soil acted as a sink of N_2O and CH_4 for most of the years (Table 9). Maris et al. (2015) found similar results in the same study site. Although there is little information on GWP in tree crops, Ruan and Robertson (2013) reported -105 kg CO_2-eq ha^{-1} in poplar. However, they included CO_2 emissions in the calculation of GWP. Only year 2015 showed positive GWP for the FI+N50 and RDI+N50 treatments. This could be explained by the exceptional climatic conditions of that year, which resulted in CH_4 emission from these treatments. Adviento-Borbe et al. (2013) found GWP in the order of those of this study in 2015 in a rice crop.

Regarding yield (expressed as oil production, Table 9), the olive tree has an alternate-bearing behaviour, which corresponds to the tendency of some fruit trees not to bear a regular and similar yield year after year (as described in Lavee, 2007). The alternate-bearing behaviour of the olive tree is so pronounced that, in combination with the exceptional weather conditions in two of the studied years, it is necessary to evaluate the oil production of the four years as a whole. Yields were within the range of values published by Maris et al. (2015); Díez et al. (2016) and Centeno et al. (2017).

In 2013 (first year of the N100 dose; the trees still had to grow in accordance with the new N dose) the FI+N100 treatment did not have the highest production. Unfortunately, due to heavy rains and hail in some cases it was not possible to study the olive harvest in 2014. In 2016 (fourth year of the N100 dose), the highest oil production was recorded (2475 kg ha^{-1}) from the FI+N100 treatment, though it was not significantly different from the RDI+N0 treatment.

The RDI strategy did not significantly decrease yield relative to the FI strategy. The same result was reported by Palese et al. (2010) in a high-density olive orchard when the reduction in water supply was applied in mid-summer, known as a less sensitive moment to water deficit. In a SHD olive orchard, Gucci et al. (2019) did observe a slight decrease in fruit yield from RDI treatments. In addition, some studies have shown no differences in oil yield between control (100% of the ETc) and RDI strategies when the water reduction is not larger than 25% of the water needs of the crop (75% of the ETc) (Alegre et al., 2002; Grijalva-Contreras et al., 2013).

The use at this site of a grape harvesting machine which is smaller than an olive harvesting one also had an effect on final yield, as it does not allow larger growth of the tree and tends to homogenize their size and therefore yield among treatments. Overall, the FI+N100 treatment showed a tendency to increase yield, without increasing GHG emissions.

The calculated greenhouse gas intensity (GHGI) was negative in all years except for treatments FI+N50 and RDI+N50 in 2015 (Table 9). Through the years, the FI+N100 treatment tended to present the most negative GHGI. Similar negative GHGI values were reported by Maris et al. (2015) in the same olive orchard. Xiang et al. (2015) found positive GHGI values lower than those of this study in 2015 during a wheat growing season.

4.5. Indirect emissions and economic and oil quality considerations

To choose the best treatment from a "Climate Smart Agriculture" viewpoint the indirect emissions need to be considered. The emissions associated to N manufacturing and transport were 1.18 kg CO_2-eq N kg^{-1} (Fertilizers Europe, n.d.). The emissions associated to water pumping were estimated considering the average value associated to the Spanish electrical mix, 321 g CO_2 kWh^{-1} (Gencat, n.d.), and the energy cost of pumping water in the Carrassumada irrigation system which is 0.5 kWh m^{-3} (Tomillero, 2019, per. com.). Resulting in an indirect emission of 145 kg CO_2 ha^{-1} for the 90 mm on average of water saved with the RDI strategy.

No water table was found at this site. Instead, there is an impermeable lutite (claystone; sedimentary rocks) layer at 60 to 80 cm. In a previous study in the same experimental field by Belguerri et al. (2016), it was determined that the sum of irrigation water plus the effective rain was about the water demand of the olive trees (ETc) during all the sampling period (April to October) in 2011 and 2012. Soil water content during the irrigation period was always below field capacity due to low precipitation and high evapotranspiration (Table 3). There was no water leaching, and therefore no nitrate loss. The analysed soil nitrate content in the central zone of the tree rows (beyond the wet bulb) was negligible.

It would be expected that treatments that involve a saving of inputs (water, N) and lead to similar results regarding GHG emissions or yields are more potentially acceptable to farmers. In this irrigation system, the price of water consists of a fixed cost of 180 € ha^{-1} yr^{-1}, and a varying cost depending on actual consumption of 0.04 € m^{-3} (Tomillero, 2019, per. com.). Since the average water saving of the RDI respect to the FI was 90 mm, the saving would only be 36 € ha^{-1} yr^{-1}. Something similar happens with N, the N20 solution has a price of 170 € t^{-1} (average price of 0.86 €/kg N; MAPA, n.d.b). The cost of applying 100 kg N ha^{-1} is therefore 85 € ha^{-1} yr^{-1}. The above values show that the farmer will be interested not so much in cost-saving with respect to these inputs, but rather in practices that can improve production in any aspect. A water price scheme that would encourage water saving, would have another result. Moreover, the considered water price does not take into account the ecological impacts of irrigation water.

As Grattan et al. (2006) concluded, the irrigation amounts that maximise production are in the range of 70-75% of ETc, and those that maximise olive oil quality, with a sustained season-long irrigation deficit, in an approximate range of 33-40% of ETc. The optimal irrigation amount will be somewhere in between and depend on the objective. The results of this study (data not shown) did not reveal any oil quality decrease in any of the tested treatments.

5. Conclusions

The soil acted mainly as a net sink of N_2O. The RDI irrigation strategy significantly mitigated emissions compared to FI. The soil acted mainly as a CH_4 sink. Methane oxidation increased with N dose in the FI treatments. The negative GHG emissions were attributed to the WFPS content and N dose appropriate to the crop needs. The effect of the treatments on yield was not conclusive.

Based on the cumulative N_2O and CH_4 emissions, there were no statistically significant differences between the irrigation strategies in terms of their effect on the GWP, GHGI, or oil production. However, increasing N tended to increase oil production without increasing emissions. Further confirmation of this tendency is necessary. In this respect, it would be particularly interesting to compare FI+N100 (the most promising treatment in terms of profitability) with the water-saving capability of an RDI+N100 strategy (not available in this study).

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Tables

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Figures

Fig. 1. Evolution of the water-filled pore space (WFPS) in 2013 (a), 2014 (b), 2015 (c) and 2016 (d), with the start and the end of the RDI period marked with dotted lines. FI: full irrigation; RDI: regulated deficit irrigation. The error bars correspond to the standard deviation.

Fig. 2. Average daily nitrous oxide (N_2O-N) fluxes sampled in 2013 (a), 2014 (b), 2015 (c) and 2016 (d) per treatment. The start and the end of the RDI period are marked with dotted lines. FI: full irrigation; RDI: regulated deficit irrigation. The error bars correspond to the standard deviation.

Fig. 3. Soil NO_3^--N content through the four studied years. FI: full irrigation; RDI: regulated deficit irrigation.

Fig. 4. Average daily methane (CH_4) fluxes during the sampling period in 2013 (a), 2014 (b), 2015 (c) and 2016 (d) per treatment. The start and the end of the RDI period are marked with dotted lines. FI: full irrigation; RDI: regulated deficit irrigation. The error bars correspond to the standard deviation.

Table 1. Effect of nitrogen fertilisation on olive yield.

Country	Olive cultivar	Years of study	Year of planting	Plantation frame (m^2)	Tree density (trees ha^{-1})	Type of irrigation	Higher fertilisation per tree (kg N $tree^{-1}$)	Range of applied N (kg N ha^{-1} yr^{-1})	Effect of N on olive yield	Observations	References
Portugal	Picual	1995-1997	1987	-	250	Non-irrigated	0.48	0-120	Not significant	N and Mg fertilisation did not affect yield, its average weight nor its fat content	Marcelo et al. (2002)
Spain	Picual	1994-2006	1997	7 x 7	204 (calculated)	Non-irrigated	1.00	0-200 (calculated)	Not significant	It seems that annual N applications are unnecessary to maintain high productivity and growth	Fernández-Escobar et al. (2009)
	Picual		1959	12 x 12	69 (calculated)		1.15	0-100 (calculated)			
Spain	Manzanilla de Sevilla	1999-2003	1989	7 x 7	204	Drip	0.40 (1999-2001) 0.60 (2002-2003)	0-82 (1999-2001) 0-122 (2002-2003) (calculated)	Significant	Cumulative yield for the experimental period increased with fertiliser dose	Morales-Sillero et al. (2009)
Portugal	Verdeal Transmontana	2003-2008	-	-	-	Non-irrigated	0.52	-	Significant	Olive yield decreased in the treatment without N application	Rodrigues et al. (2011)
Morocco	Moroccan Picholine	2010-2011	2005	10 x 10	100 (calculated)	Non-irrigated	1.00	0-100 (calculated)	Not significant	N applications did not affect yield	Bouhafa et al. (2014)
	Moroccan Picholine		1979	9 x 9	123 (calculated)	Non-irrigated		0-123 (calculated)	Significant	N fertiliser improved yield, yield efficiency and olive oil content	
	Arbequina		2007	3 x 5	667 (calculated)	Non-irrigated		0-667 (calculated)	Not significant	N negatively affected the olive oil quality	
Spain	Picual	2008-2010	2005	8 x 6	208	Drip	0.66	0.4-138	Not significant	'Picual' did not respond to N applications	Centeno et al. (2017)
	Arbequina		2006	4 x 1.5	1667		0.22	0.4-368	Not significant	Olive oil quality was negatively affected with high N doses	
Israel	Barnea	2011-2016	2007	4 x 7	360	Drip	0.83	0-300	Significant	150 kg N ha^{-1} was the best tested treatment	Haberman et al. (2019)

Table 2. Average chemical soil properties at the beginning of the study, and soil granulometric analysis.

	Depth 0-25 cm
Chemical properties	
$CaCO_3$ (%)	26
Gypsum content (%)	5.4
Organic matter (Walkley-Black; %)	2.0
pH (1:2.5 water extract)	8
EC (1:5 water extract; dS m^{-1})	0.7
NO_3^--N (colorimetry; ppm)	11
P (Olsen; ppm)	32
K (Ammonium acetate extract; ppm)	169
Granulometric analysis	
Clay (%)	24
Fine silt (%)	31
Coarse silt (%)	14
Fine sand (%)	29
Coarse sand (%)	2
USDA textural class	Loam

Table 3. Monthly ETo, rainfall, irrigation (FI: full irrigation; RDI: regulated deficit irrigation) and applied N fertiliser per year.

Year	Month	ETo (mm)	Rainfall (mm)	Irrigation (mm)		Fertiliser (kg N ha^{-1})	
				FI	RDI	N50	N100
2013	April	94	68	29	19	16	33
	May	124	19	47	43	17	35
	June	152	50	57	63	13	26
	July	183	26	73	45	0	0
	August	151	4	90	42	0	0
	September	110	15	43	30	8	15
	October	72	19	23	24	0	0
	Total	886	201	362	266	54	109
2014	April	110	72	21	35	0	0
	May	137	28	80	67	14	25
	June	165	13	66	61	26	51
	July	162	44	78	46	6	13
	August	148	28	90	43	0	0
	September	96	96	11	8	7	17
	October	67	19	9	10	0	0
	Total	885	300	355	270	53	106
2015	April	111	10	53	52	0	0
	May	156	3	49	58	21	34
	June	170	38	79	87	24	51
	July	185	53	72	38	0	0
	August	152	17	79	38	0	0
	September	97	11	25	24	8	17
	October	64	17	15	18	0	0
	Total	935	149	372	315	53	102
2016	April	105	57	35	35	0	0
	May	134	54	42	42	14	28
	June	166	3	80	73	20	40
	July	187	0	102	50	11	23
	August	162	0	109	44	0	0
	September	112	4	62	56	6	12
	October	58	41	17	27	0	0
	Total	924	159	447	327	51	103

Table 5. Average cumulative N_2O-N emissions plus minus the standard deviation per treatment and year, and ANOVA of the effect of irrigation, fertilisation and their interaction studied only for the N0 and N50 doses. FI: full irrigation; RDI: regulated deficit irrigation.

Treatment	Cumulative N_2O-N (g ha^{-1})				
	2013	2014	2015	2016	All years together
FI+N0	-358 ± 340b	-917 ± 405a	-234 ± 89b	-708 ± 190ab	-519 ± 256ab
FI+N50	266 ± 222a	-796 ± 500a	174 ± 200a	-568 ± 110ab	-167 ± 258a
FI+N100	-1948 ± 660c	-537 ± 151a	137 ± 65a	-471 ± 49a	-738 ± 231b
RDI+N0	-	-684 ± 289a	-844 ± 158c	-499 ± 90a	-709 ± 179b
RDI+N50	-	-447 ± 261a	-213 ± 62b	-966 ± 118b	-456 ± 147ab
	ANOVA of N0 and N50				
Irrigation (I)	-	ns	*	ns	ns
Nitrogen (N)	*	ns	*	ns	*
I x N	-	ns	ns	ns	ns

Within columns, averages followed by the same letter are not significantly different according to Tukey's test ($p<0.05$). *, ns: significant and non-significant at the 0.05 probability level.

Table 6. Average cumulative N_2O-N emissions plus minus the standard deviation per year and separated per treatment factor (irrigation and fertilisation). FI: full irrigation; RDI: regulated deficit irrigation.

Treatment factor	Cumulative N_2O-N (g ha^{-1})			
	2013	2014	2015	2016
N0	-358 ± 340b	-751 ± 347a	-539 ± 124b	-603 ± 140a
N50	-266 ± 222a	-649 ± 381a	-19 ± 131a	-767 ± 114a
N100	-1948 ± 660c	-537 ± 151a	137 ± 65a	-471 ± 49a
FI	-	-856 ± 453a	-30 ± 145a	-638 ± 150a
RDI	-	-544 ± 420a	-528 ± 110b	-732 ± 104a

Averages in a column followed by the same letter are not significantly different based on Tukey's test ($p<0.05$).

Table 7. Average cumulative CH_4 emissions plus minus the standard deviation per treatment and year, and ANOVA of the effect of irrigation, fertilisation and their interaction studied only for the N0 and N50 doses. FI: full irrigation; RDI: regulated deficit irrigation.

Treatment	Cumulative CH_4 (kg ha^{-1})				
	2013	2014	2015	2016	All years together
FI+N0	-21 ± 35a	-144 ± 58a	55 ± 23a	-1.66 ± 0.35ab	-27 ± 29a
FI+N50	-138 ± 49b	-114 ± 45a	50 ± 15a	-1.69 ± 0.28ab	-62 ± 27a
FI+N100	-498 ± 67c	-154 ± 35a	-343 ± 130b	-1.62 ± 0.12a	-258 ± 58b
RDI+N0	-	-136 ± 31a	-148 ± 182b	-1.31 ± 0.20a	-115 ± 71a
RDI+N50	-	-106 ± 37a	65 ± 35a	-2.02 ± 0.23b	-13 ± 24a
	ANOVA of N0 and N50				
Irrigation (I)	-	ns	*	ns	ns
Nitrogen (N)	*	ns	*	*	*
I x N	-	ns	ns	ns	ns

Within columns, averages followed by the same letter are not significantly different according to Tukey's test ($p<0.05$). *, ns: significant and non-significant at the 0.05 probability level.

Table 8. Average cumulative CH_4 emissions plus minus the standard deviation per year and separated per treatment factor (irrigation and fertilisation). FI: full irrigation; RDI: regulated deficit irrigation.

Treatment factor	Cumulative CH_4 (kg ha^{-1})			
	2013	2014	2015	2016
N0	-21 ± 35a	-140 ± 45a	-47 ± 103b	-1.49 ± 0.28a
N50	-138 ± 49b	-110 ± 41a	72 ± 25a	-1.86 ± 0.26b
N100	-498 ± 67c	-154 ± 35a	-343 ± 130c	-1.62 ± 0.12a
FI	-	-129 ± 51a	52 ± 19a	-1.68 ± 0.32a
RDI	-	-119 ± 34a	-42 ± 109b	-1.66 ± 0.22a

Averages in a column followed by the same letter are not significantly different based on Tukey's test ($p<0.05$).

Table 9. Global warming potential (GWP), oil production and greenhouse gas intensity (GHGI) per treatment and year. FI: full irrigation; RDI: regulated deficit irrigation.

Treatment	GWP (kg CO_2-eq ha^{-1})				Oil production (kg ha^{-1})			GHGI (kg CO_2-eq kg^{-1} oil production)		
	2013	2014	2015	2016	2013	2015	2016	2013	2015	2016
FI+N0	-477a	-3716a	-1262ab	-253ab	2020ab	606a	2020b	-0.24a	-2.08ab	-0.13ab
FI+N50	-3046b	-3698a	1533ab	-212ab	2491a	455a	1970b	-1.22a	3.37a	-0.11ab
FI+N100	-13025c	-4468a	-5966c	-182a	2087ab	657a	2475a	-6.24b	-9.08b	-0.07a
RDI+N0	-	-3610a	-2296bc	-181a	1784b	640a	2121ab	-	-3.59ab	-0.09a
RDI+N50	-	-2839a	1715a	-338b	2087ab	707a	1885b	-	2.43a	-0.18b

Within columns, averages followed by a different letter are significantly different according to Tukey's test ($p<0.05$). The oil production of 2014 is not included because the harvest was lost due to storms and hail.

Highlights

- Olive crop was a net sink of N_2O and CH_4 at water-filled pore space above 60%
- CH_4 oxidation increased significantly with increasing N doses under full irrigation
- Reducing irrigation decreased emissions without decreasing yield in 2015
- Full irrigation+max. N dose did not increase emissions and tended to increase yield

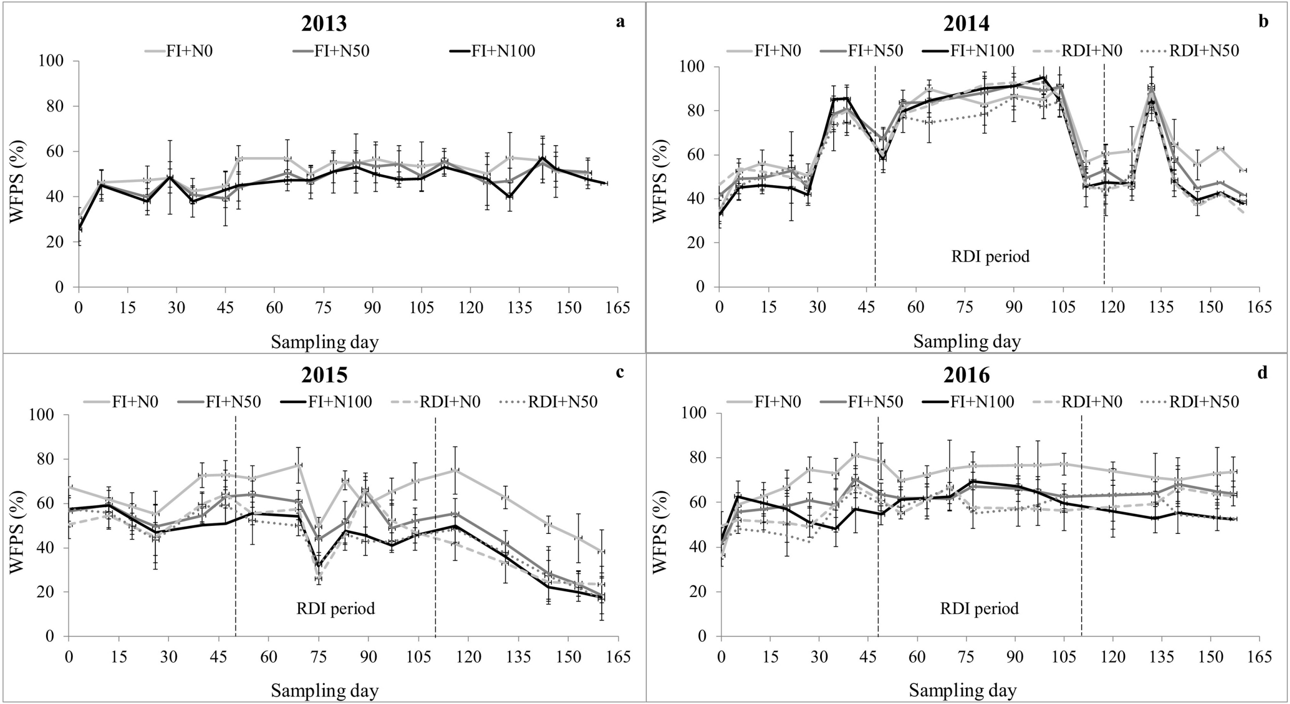
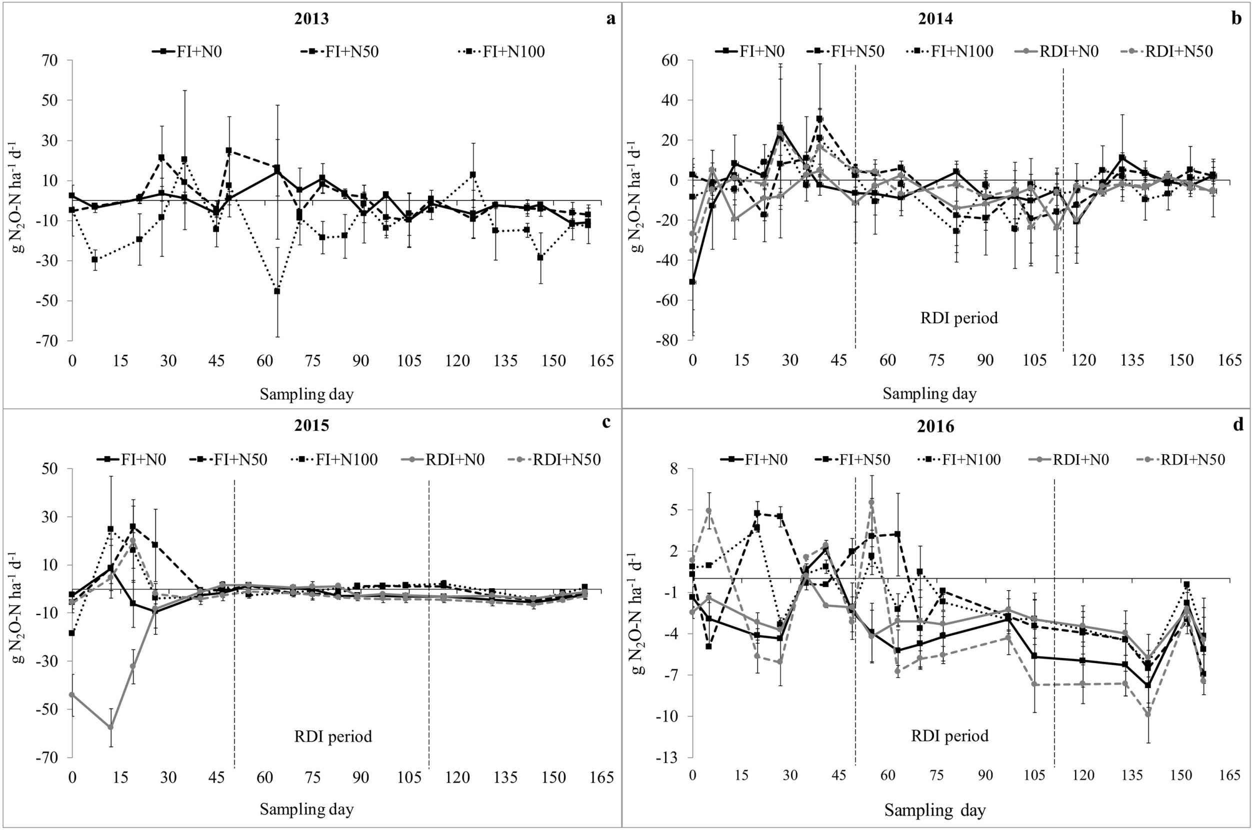
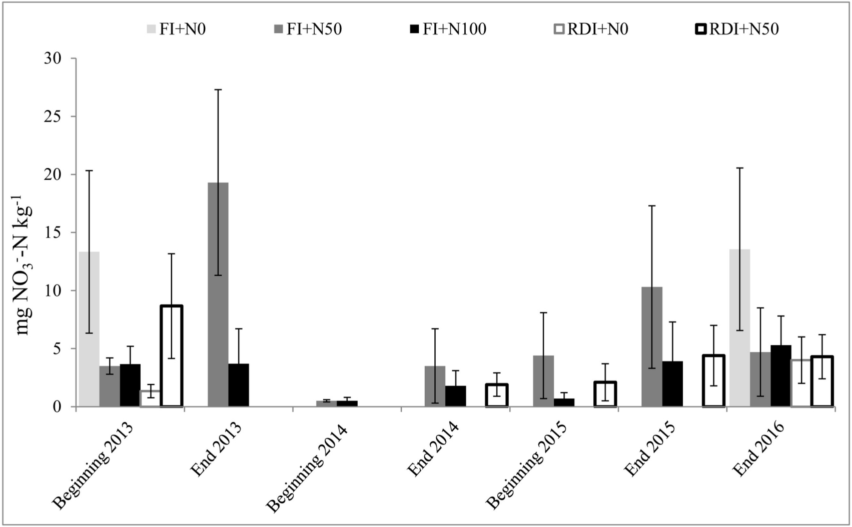

2013
a
FI+N0
FI+N50
FI+N100
WFPS (%)
Sampling day
2014
b
FI+N0
FI+N50
FI+N100
RDI+N0
RDI+N50
RDI period
WFPS (%)
Sampling day
2015
c
FI+N0
FI+N50
FI+N100
RDI+N0
RDI+N50
RDI period
WFPS (%)
Sampling day
2016
d
FI+N0
FI+N50
FI+N100
RDI+N0
RDI+N50
RDI period
WFPS (%)
Sampling day

Figure 1



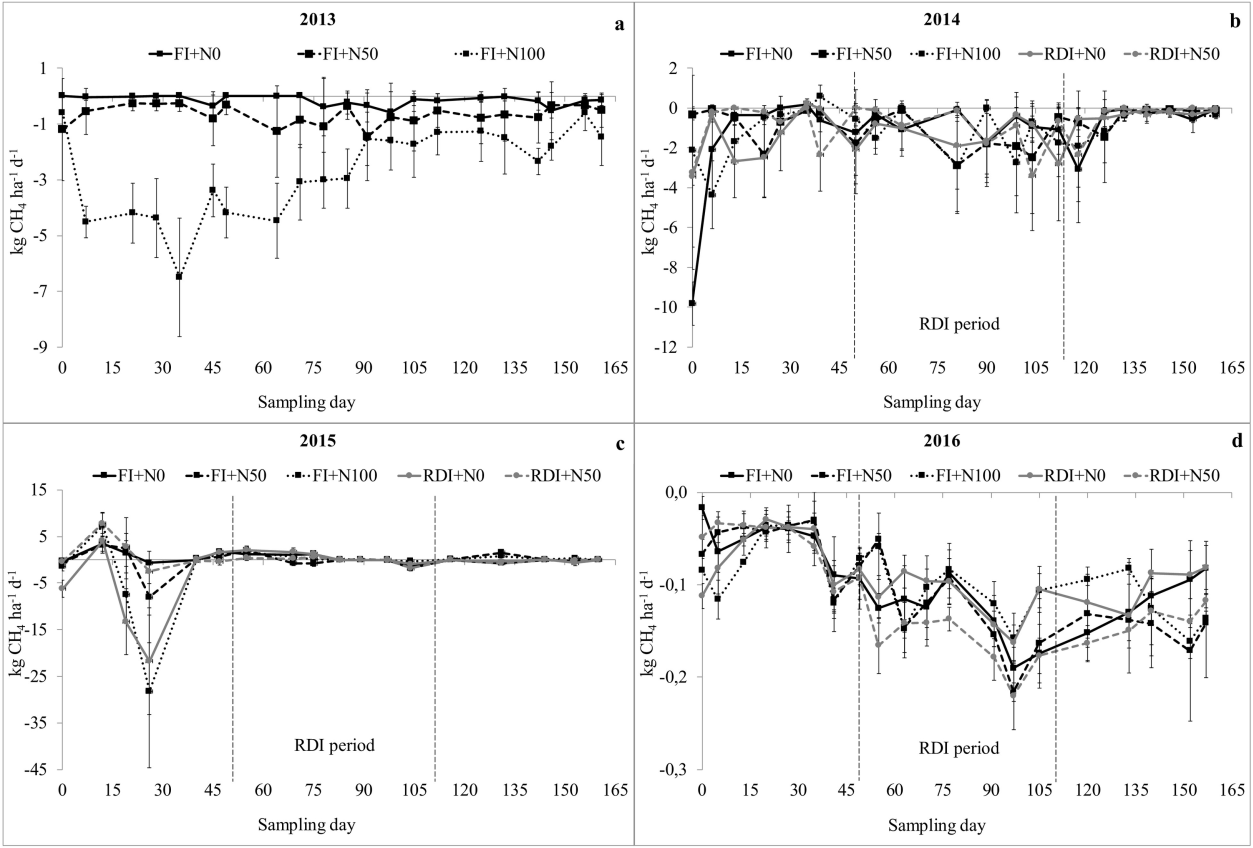
2013
a
FI+N0
FI+N50
FI+N100
g N2O-N ha-1 d-1
Sampling day
2014
b
RDI+N0
RDI+N50
RDI period
2015
c
2016
d

Figure 2



FI+N0
FI+N50
FI+N100
RDI+N0
RDI+N50
30
25
20
15
10
5
0
mg NO_3^--N kg^{-1}
Beginning 2013
End 2013
Beginning 2014
End 2014
Beginning 2015
End 2015
End 2016

Figure 3



2013
a
FI+N0
FI+N50
FI+N100
kg CH4 ha-1 d-1
Sampling day
2014
b
RDI+N0
RDI+N50
RDI period
2015
c
2016
d

Figure 4